

This study investigates magnetic system in the ST-40-type Hall-effect thruster and its modification with magnetic shielding of the accelerating channel. The task addressed relates to the lack of systematic quantitative data on the influence of magnetic shielding techniques on the topology of the magnetic field in the channel. The associated parameters that affect the erosion of the walls and the stability of the engine operating modes remain undefined.

This work reports mathematical modeling of the magnetic field topology for the engine of the classical scheme and two variants of magnetic shielding: with an external magnetic shield and using a magnetically soft hollow anode. Spatial distributions of the radial component of the field induction were determined and induction gradients along the axis of the accelerating channel were derived. It is shown that for the classical scheme the maximum induction gradient is about 0.67 T/m. The external magnetic shield increases it to 1.17 T/m, and the hollow anode – to 1.29 T/m, that is, 1.7–1.9 times.

The results are explained by a change in magnetic resistance and redistribution of magnetic flux, which leads to deformation of the lines of force, their orientation along the dielectric walls of the channel, and removal of the maximum magnetic field induction beyond the engine section. A distinctive feature of this study is a direct quantitative comparison of the magnetic field topology for different design schemes on a single geometric and current basis, which made it possible to objectively assess the effectiveness of each variant of magnetic shielding.

The implementation of results is possible in the design and optimization of magnetic systems of Hall engines of medium power class under conditions close to laboratory and ground tests. Their application could contribute to reducing erosion, increasing discharge stability, and increasing the resource

Keywords: *Hall-effect thruster, magnetic shielding, magnetic field topology, acceleration channel, simulation*

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THE INFLUENCE OF MAGNETIC SHIELDING TECHNIQUE ON THE MAGNETIC FIELD TOPOLOGY IN AN ACCELERATING CHANNEL OF THE HALL-EFFECT THRUSTER

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1. Introduction

Hall thrusters are one of the most common types of electrojet engines, widely used in modern space propulsion systems on board spacecraft. These propulsion systems are used to solve the following tasks: stabilization and orientation, maintaining parameters and orbit correction, orbital maneuvering. Their popularity is due to the combination of relatively high thrust efficiency, simplicity of design, reliability, and the possibility of long-term operation in outer space. At the same time, many years of operating experience and numerous laboratory studies have revealed a number of fundamental problems inherent in this class of engines.

The main problems of Hall thrusters include intensive erosion of the dielectric walls of the accelerating channel, as well as the occurrence of unstable operating modes, which are accompanied by an increase in the average value of the discharge current and an increase in the amplitude of its oscillations. These phenomena lead to a decrease in the effi-

ciency and a limitation of the engine resource. Under current conditions, when there is a steady trend towards an increase in the duration of active existence of spacecraft and increasing requirements for their energy efficiency, these problems are becoming particularly urgent.

The key factor determining the intensity of erosion processes and the conditions for the stability of the discharge in the Hall-effect thruster is the topology of the magnetic field in the accelerating channel. It is the configuration of the magnetic lines of force, the magnitude and spatial distribution of the radial component of the magnetic field induction that determine the localization of the ionization and acceleration zones, the processes of electron transfer, and the nature of the interaction of the plasma with the walls of the channel. In this regard, the design and optimization of the magnetic system of the Hall-effect thruster are considered one of the most effective ways to increase its resource and operational characteristics.

One promising area for improving Hall-effect thrusters is the use of magnetic shielding of the accelerating channel,

which makes it possible to purposefully change the topology of the magnetic field in order to reduce the flow of charged particles on the dielectric walls and increase the stability of the discharge. However, the variety of structural solutions for magnetic shielding and the lack of unified approaches to the formation of magnetic topology complicate the practical use of this approach at the stage of engine design.

In this context, mathematical modeling of the topology of the magnetic field in the accelerating channel of a Hall-effect thruster is an important scientific and applied tool that makes it possible to study the influence of the design parameters of the magnetic system on the characteristics of the magnetic field without conducting resource-intensive experiments. Such studies form the basis for devising practical recommendations for the design of magnetic systems of Hall-effect thrusters, aimed at reducing erosion, expanding the area of stable operating modes, and increasing the overall efficiency of the engine.

Thus, scientific research into modeling and analysis of the topology of the magnetic field in the accelerating channel of Hall thrusters with various shielding options is relevant. It meets modern requirements for electro-reactive installations and has practical significance for the evolution of space technology.

2. Literature review and problem statement

In Hall-effect thrusters, the ionization of the working gas and the acceleration of charged particles occur under conditions of crossed radial magnetic and longitudinal electric fields, the formation of which is determined by the design and parameters of the magnetic system of the engine. In work [1], it is shown that the topology of the magnetic field significantly affects the processes of electron transfer, the position of the ionization zone and the main operating parameters of the engine. However, in the cited work, attention focuses on the generalized principles of magnetic field formation without a detailed analysis of the influence of specific design solutions of the magnetic system on the spatial distribution of the radial component of the magnetic field induction in the accelerating channel. The reason is the complexity of experimental verification of such distributions and the limitations of available computational models at the time of the research.

In [2, 3], the concept of magnetic shielding of the walls of the accelerating channel of the Hall-effect thruster is substantiated and the possibility of orienting the magnetic induction lines along dielectric surfaces is shown, which significantly reduces channel erosion. In [4], it was experimentally confirmed that the engine life was increased when using the appropriate magnetic topology. However, in those studies, the issues of the quantitative relationship between the geometric and electromagnetic parameters of the magnetic system and the actually formed spatial distribution of the radial component of magnetic induction remained unresolved. The reason is that the work was mainly focused on proving the effect of reducing erosion and engine life, while the structural features of the magnetic field formation were considered as an accompanying factor, without a systematic parametric comparison of different design schemes.

In [5, 6], the influence of the magnetic field gradient in the accelerating channel on the discharge characteristics and operating parameters of conventional Hall-effect thrusters was studied. It was shown that an increase in the magnetic field gradient leads to a decrease in the discharge current and a decrease in the amplitude of its oscillations. However, the

authors did not consider designs with magnetic shielding of the channel, and the results were obtained for classical engine circuits. This limits the possibility of extrapolating the conclusions to engines with a modified magnetic topology. The reason is the fundamental difference in the mechanisms of magnetic field formation in shielded and unshielded designs.

A direct experimental connection between the magnetic field distribution and fluctuations in plasma parameters in the accelerating channel was demonstrated in work [7]. The authors showed that a change in the magnetic flux density affects the electron mobility and, accordingly, the stability of the discharge. However, the work does not offer practical recommendations for the formation of magnetic topology, which could be directly used in the design of magnetic systems of motors with magnetic shielding. This is due to the complexity of the isolated influence of individual elements of the magnetic system under real experimental conditions.

Numerical studies reported in [8] showed the possibility of low-frequency "breathing" oscillations of the discharge current in the classical Hall-effect thruster SPT-100 depending on the parameters of the magnetic system. However, the results were obtained for a specific classical design and do not take into account the features of the magnetic shielding of the channel. The reason is the authors' focus on the validation of the numerical model, rather than on the analysis of various options for the structural implementation of the magnetic system.

Further development of the concept of magnetic shielding was implemented within the framework of NASA (National Aeronautics and Space Administration) programs when designing HERMeS-type engines [9, 10]. In [11, 12], the influence of the magnetic field gradient and its spatial displacement on the electron transfer processes and discharge stability was investigated. It was shown that the displacement of the maximum of the radial component of magnetic induction beyond the channel section significantly changes the plasma characteristics. At the same time, those studies focused on high-power engines (over 10 kW) with a specific architecture of the magnetic system. The issues of applicability of the established laws to low- and medium-power engines, as well as to designs that combine elements of classical and shielded schemes, remain unresolved. The objective reason is the high cost of experimental development of new configurations and the complexity of scaling the results for powerful engines.

In [7], the influence of the magnetic field gradient on the characteristics of a magnetically shielded Hall-effect thruster was investigated and a relationship was established between the gradient magnitude and the discharge parameters. However, in the work, no comparative analysis of alternative methods of structural implementation of magnetic shielding was carried out, and the geometry of the magnetic system was taken as given. The reason is the focus of the study on plasma processes and engine performance, while the variability of the structural schemes of the magnetic system was not the subject of a separate study.

Despite a significant body of research, there are no systematic studies on the quantitative relationship between the parameters of the magnetic system and the topology of the field. This is especially true for motors with combined shielding schemes. The reason is the complexity of conducting a comparative analysis of different variants of magnetic systems within the framework of one engine size and the lack of unified calculation approaches.

Our review of the literature [1–12] indicates the lack of systematic quantitative studies on the influence of various

variants of magnetic shielding on the topology of the magnetic field in the accelerating channel of Hall-effect thrusters, especially for combined designs. This allows us to state an unsolved problem: there are no quantitative data linking the design parameters of the magnetic system with the spatial distribution of the radial component of the magnetic field, which determines the erosion of the walls and the stability of the engine operating modes.

3. The aim and objectives of the study

The purpose of our study is to establish patterns in the influence of various techniques of magnetic shielding of the accelerating channel on the topology of the magnetic field of the ST-40 type Hall-effect thruster, which is considered as a prototype of an engine of a classical design scheme. This will make it possible to devise practical recommendations and methodological approaches to the design of magnetic systems of Hall-effect thrusters with magnetic shielding of the accelerating channel. Such recommendations are aimed at the formation of a radial component of magnetic induction in the ionization and acceleration zone, to reduce erosion of the channel walls and increase the resource and stability of engine operation.

To achieve the set goal, it is necessary to solve the following tasks:

- to build a computational model of the magnetic system and perform modeling of the magnetic field topology and determine the spatial distribution of the radial component of magnetic field induction in the accelerating channel of the ST-40 Hall-effect thruster, made according to the classical scheme;

- to build a computational model of the magnetic system of the engine with magnetic shielding of the accelerating channel and perform modeling of the magnetic field topology and determine the spatial distribution of the radial component of magnetic induction.

4. The study materials and methods

The object of our study is the magnetic system of the ST-40 type Hall-effect thruster and its modification with magnetic shielding of the accelerating channel. The Hall-effect thruster ST-40, designed by Flight Control LLC (Ukraine) [13], was chosen as a basic prototype with the classical structure.

The principal hypothesis assumes that changing the design of the magnetic system, in particular the use of different variants of magnetic shielding of the accelerating channel, leads to a significant change in the topology of the magnetic field. First of all, this concerns the distribution of the radial component of the magnetic field induction, which determines the processes of ionization and acceleration of particles.

The following assumptions are adopted in the study:

- the magnetic field in the accelerating channel is quasi-stationary;
- the effect of plasma on the distribution of the magnetic field is not taken into account;
- the magnetic core materials operate in a range that does not lead to saturation.

The accepted simplifications include the use of an axisymmetric magnetic field model, a planar calculation scheme, and a two-dimensional model of the magnetic field topology in the accelerating channel.

The mathematical modeling of the magnetic field was performed in the magnetostatic formulation based on Maxwell's equations (1) and (2):

$$\nabla \times H = J, \tag{1}$$

$$\nabla \cdot B = 0, \tag{2}$$

at relationship (3)

$$B = \mu(H) \cdot H, \tag{3}$$

where J is the current density; B is the magnetic induction; $\nabla \times$ is the rotor operator; H is the magnetic field strength; μ is the magnetic permeability of vacuum.

For numerical implementation, the FEMM 4.2 (Finite Element Method Magnetics) software [14] was used, which is based on the finite element method (FEM). The calculation was carried out through the magnetic vector potential A , which automatically satisfies the condition $\nabla \cdot B = 0$. The problem was reduced to solving equation (4)

$$\nabla \times (1 / \mu(B) \nabla \times A) = J. \tag{4}$$

The calculation domain was discretized into triangular finite elements. The field in each element was approximated by linear basis functions at the nodal potential values. After the variational formulation, a sparse system of linear equations was formed, which was solved by the method of preconditioned conjugate gradients (PCG). After obtaining the nodal potential values A , the components of the magnetic induction $B = \nabla \times A$ were calculated. The "patch recovery" algorithm was used to smooth the results.

To study the topology of the magnetic field in the accelerating channel of the Hall-effect thruster of the classical scheme, the ST-40 prototype was used. The calculation scheme for modeling the magnetic field is shown in Fig. 1. The modeling was carried out for the section of the accelerating channel between the central coil and one of the side coils of the magnetic system.

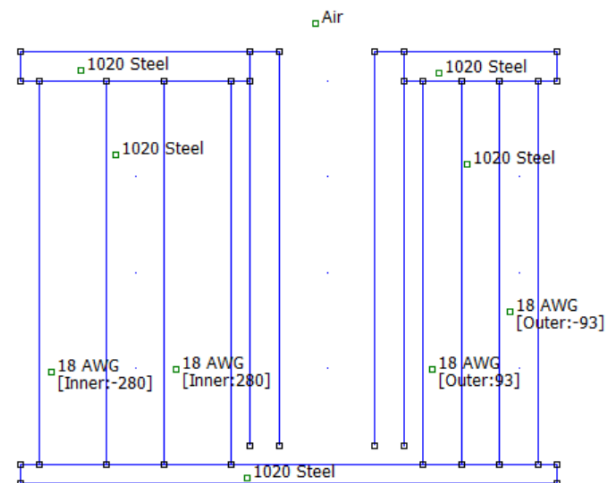


Fig. 1. Calculation scheme for modeling the topology of the magnetic field in a classical Hall-effect thruster

The following main design parameters were used during the simulation:

- diameter of the inner pole of the magnetic system – 24 mm;
- inner diameter of the outer pole – 56 mm;

- width of the accelerating channel – 10 mm;
- length of the accelerating channel – 40 mm;
- diameter of the core of the inner coil – 6 mm;
- number of turns of the inner coil – 280;
- number of outer coils – 3;
- diameter of the core of the outer coils – 4 mm;
- number of turns of each outer coil – 93;
- width of the magnetic poles – 3.0 mm;
- gap between the magnetic poles – 16 mm;
- material of the magnetic core – steel 1020.

The total number of ampere-turns of the magnetic system was set to the same 280 for all design options in order to ensure the correctness of the comparison.

The main idea of magnetic shielding of the dielectric walls of the accelerating channel of the Hall-effect thruster is to form such a configuration of the magnetic field, in which the lines of force of magnetic induction in the channel section are oriented mainly parallel to the channel walls. This made it possible to reduce the intensity of ion bombardment of the walls and, accordingly, the degree of their erosion [2, 3].

Our study considered two options for the structural implementation of magnetic shielding of the accelerating channel.

The first option involves the use of an external magnetic shield located outside the walls of the accelerating channel with a certain gap relative to the magnetic poles. The calculation scheme of this configuration is shown in Fig. 2. In such a design, the magnetic shield partially shunts the magnetic gap between the poles of the magnetic system. Therefore, to achieve a given maximum magnetic field induction in the gap, it is necessary to increase the currents in the inner and outer coils compared to the classical scheme. According to the recommendations given in [2, 3, 7], in the magnetic pole zone, the dielectric walls of the channel have a conical shape. Within the limits of the adopted model, the shape of the walls does not affect the results of the magnetic field simulation.

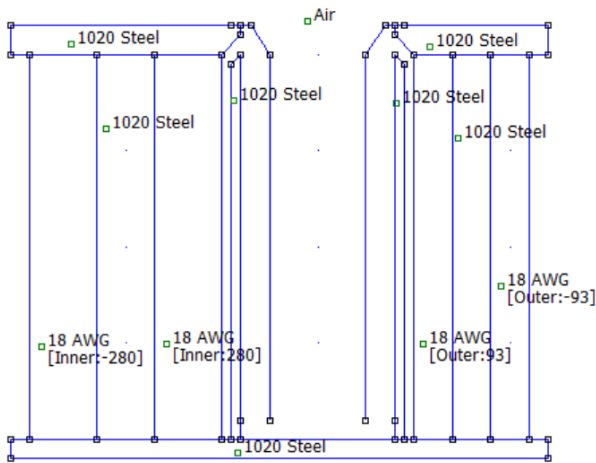


Fig. 2. Calculation scheme for modeling the magnetic field topology in a Hall-effect thruster with magnetic shielding

The second variant of magnetic shielding is implemented by using a soft magnetic hollow anode. The design scheme of such a structure is shown in Fig. 3. In this case, the anode, made of soft magnetic material, closes the magnetic gap between the poles of the magnetic system. Under the anode, it is envisaged to place a gas distributor, which ensures the supply of working gas to the accelerator channel through a system of holes in the anode.



Fig. 3. Calculation scheme for modeling the topology of magnetic field induction in a Hall-effect thruster with a hollow anode

For all variants, identical boundary conditions, dimensions of the calculation domain and convergence criteria of the solution were used.

After completion of the numerical calculation, the following was carried out:

- construction of distributions of the radial component of induction along the channel axis;
- determination of the coordinates of the maximum of induction;
- estimation of the magnetic field gradient;
- analysis of the configuration of the lines of force.

The adequacy of the numerical model was checked by:

- control of the convergence of the solution when the grid is condensed;
- comparison of the integral parameters of the magnetic field with analytical estimates for a simplified configuration;
- verification of the fulfillment of boundary conditions and the physical correctness of the field distribution.

For all variants of the designs, a single modeling procedure was used, which ensured the reproducibility of the results and the possibility of their correct comparison.

5. Results of research on the topology of the magnetic field in the Hall-effect thruster

5.1. Topology of the magnetic field in the accelerating channel of a classical motor

The results of mathematical modeling of the topology of magnetic field induction in the accelerating channel of the ST-40 Hall-effect thruster, which was considered as a prototype, are shown in Fig. 4. The modeling was performed for three variants of the distribution of the number of ampere-turns between the internal and external coils of the magnetic system while maintaining the total value of ampere-turns.

Fig. 4, *a* shows the topology of magnetic field induction in the engine's acceleration channel under the condition that only the inner coil is active, through which a current of $I_{em1} = 1$ A is passed, which corresponds to the number of ampere-turns of 280.

Fig. 4, *b* shows the magnetic field distribution for the case when only the outer coil with a current of $I_{em1} = 3.02$ A is active, which also corresponds to the number of ampere-turns of 280.

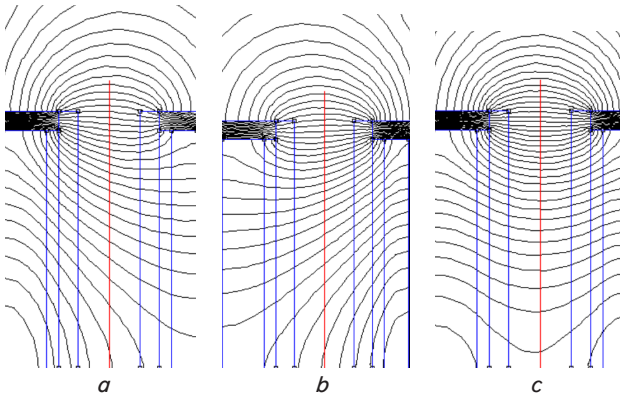


Fig. 4. Topology of the magnetic field in the accelerating channel at different values of currents in the inner and outer coils: *a* – only the inner coil is active; *b* – only the outer coil is active; *c* – simultaneous operation of the inner and outer coils

Fig. 4, *c* shows the topology of the magnetic field in the accelerating channel of the motor during simultaneous operation of the inner and outer coils with currents $I_{em1} = 0.5$ A and $I_{em2} = 1.51$ A, respectively, while the total number of ampere-turns of the magnetic system remains equal to 280.

The distribution of the magnetic field induction along the axis of the accelerating channel of the motor of the classical scheme for the three considered options for the current ratios in the coils of the magnetic system is shown in Fig. 5.

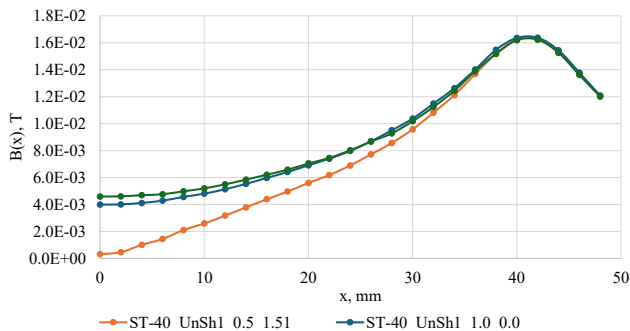


Fig. 5. Plots of the distribution of radial magnetic field induction along the accelerating channel of the ST-40 prototype engine: ST-40_UnSh1_0.5_1.51 – currents $I_{em1} = 0,5$ A, $I_{em2} = 1,51$ A; ST-40_UnSh1_1.0_0 – currents $I_{em1} = 1,0$ A, $I_{em2} = 0$ A; ST-40_UnSh1_0.0_3.0 – currents $I_{em1} = 0$ A, $I_{em2} = 3,0$ A

The plots shown in Fig. 5 allowed us to compare the position of the maximum magnetic field induction and the nature of its change along the accelerating channel for each of the considered coil power supply options at a fixed total value of the ampere-turns of the magnetic system.

5. 2. Topology of the magnetic field in the accelerating channel of the engine with magnetic shielding

The results of modeling the topology of the magnetic field in the accelerating channel and in the section region of the Hall-effect thruster with the first variant of magnetic shielding are illustrated in Fig. 6.

Fig. 6 shows the configuration of magnetic lines of force in the accelerating channel and near the output section of the engine.

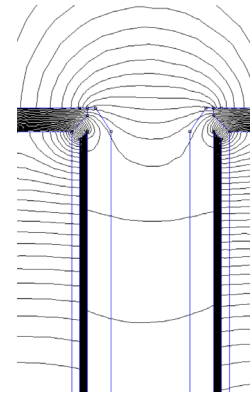


Fig. 6. Topology of the magnetic field in the accelerating channel and at the engine cut when using magnetic shielding

Fig. 7 shows a plot of the magnetic field induction distribution along the axis of the accelerating channel of the ST-40MS Hall-effect thruster using a magnetic screen. For comparison, Fig. 7 also depicts the corresponding plot of the magnetic field induction distribution for the classic ST-40 Hall-effect thruster, which was considered as a prototype.

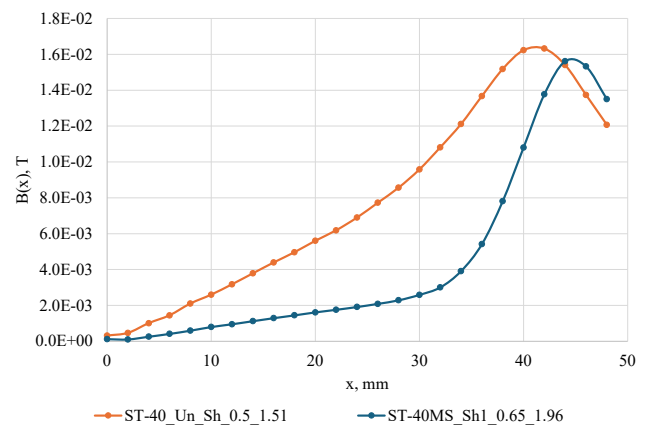


Fig. 7. Distribution of magnetic field induction along the axis of the accelerating channel of Hall-effect thrusters ST-40 and ST-40MS: ST-40_UnSh_0.5_1.51 – channel without magnetic shielding; ST-40MS_Sh1_0.65_1.96 – channel with magnetic shielding

The topology of magnetic field induction in the accelerating channel of the Hall-effect thruster using the second variant of magnetic shielding, a soft magnetic hollow anode, is shown in Fig. 8. The calculations were performed at the values of the currents of the inner and outer coils $I_{em1} = 0.61$ A and $I_{em2} = 2.3$ A, respectively, which ensured the symmetry of the magnetic field configuration relative to the channel axis.

As a result of mathematical modeling, plots of the magnetic field induction distribution along the accelerating channel of the Hall-effect thruster were also constructed for different positions of the hollow anode relative to the base of the channel. Variants with distances of 20, 24, and 28 mm were considered. The corresponding plots are shown in Fig. 9. In the same Fig. 9, for comparison, a plot of the magnetic field induction distribution obtained for the first variant of magnetic shielding is depicted.

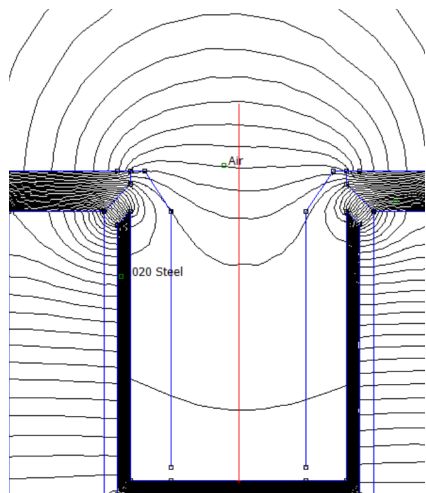


Fig. 8. Topology of magnetic field induction during magnetic shielding using a hollow anode

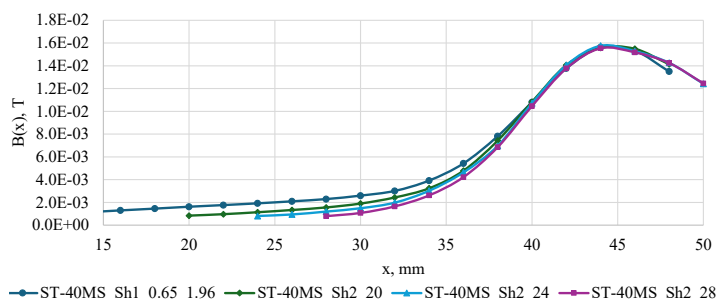


Fig. 9. Distribution of magnetic field induction along the axis of the accelerating channel of the ST-40MS Hall-effect thruster: ST-40MS_Sh1_0.65_1.96 – first variant of magnetic shielding; ST-40MS_Sh2_20 – second variant of shielding, anode coordinate – 20 mm; ST-40MS_Sh2_24 – second variant of shielding, anode coordinate – 24 mm; ST-40MS_Sh2_28 – second variant of shielding, anode coordinate – 28 mm

The graphical results illustrated in Fig. 6–9 allowed us to compare the nature of the magnetic field induction distribution along the accelerating channel for different variants of magnetic shielding and the position of the hollow anode.

6. Discussion of results based on modeling the topology of the magnetic field in the accelerating channel of the Hall-effect thruster

The modeling results obtained in our work allowed us to analyze the influence of the configuration of the magnetic system and the variants of magnetic shielding on the distribution of the magnetic field induction in the accelerating channel. This makes it possible to assess the effectiveness of the proposed design solutions from the point of view of achieving the research goal and compare them with the results known from the literature [2–4, 7].

The results obtained in the process of modeling the topology of the magnetic field in the accelerating channel of the Hall-effect thruster of the classical scheme (Fig. 4) showed that a change in the ratio between the number of ampere-turns of the internal and external coils of the magnetic system leads to a significant deformation of the topology of the magnetic field in the accelerating channel. In this case, the

nature of the distribution of magnetic lines of force changes both in shape and in the degree of symmetry relative to the longitudinal axis of the channel.

Our results (Fig. 4, 5) indicate that to ensure symmetry of the topology of magnetic field induction relative to the axis of the accelerating channel, it is necessary to fulfill the condition of equality of the number of ampere-turns of the internal and external coils of the motor magnetic system. This case corresponds to the configuration shown in Fig. 4, c and is consistent with the nature of the distribution of magnetic field induction along the axis of the channel shown in Fig. 5.

Analysis of the maximum values of magnetic field induction in the elements of the magnetic system revealed that under all modes it does not exceed the saturation level of steel 1020. This applies to the central and external cores, poles, and the lower magnetic core. This indicates the adequacy of the selected geometric dimensions of the magnetic system and the correctness of the adopted design parameters from the point of view of magnetic performance.

The magnetic field induction distribution plot along the axis of the accelerating channel (Fig. 5), built on the basis of the simulation results, allowed us to determine the magnitude of the magnetic field induction gradient for the engine of the classical scheme. In the channel section 30–40 mm long, which corresponds to the region of maximum induction values, the gradient is 0.672 T/m, which can be used as a baseline for further comparison with magnetic shielding options.

The results of modeling the topology of the magnetic field in the accelerating channel of the engine with a magnetic shield located outside the dielectric walls of the channel (Fig. 6) demonstrate a significant change in the configuration of magnetic lines of force compared to the classical scheme without shielding. In particular, in the region of maximum induction values, the lines of force are oriented almost along the walls of the accelerating channel, which corresponds to the principle of magnetic shielding of dielectric surfaces.

Comparative analysis of the magnetic field induction distribution plots along the channel axis (Fig. 7) reveals that the use of a magnetic screen leads to a change in the shape of the induction distribution, an increase in the magnetic field gradient, and the displacement of the maximum of the induction beyond the engine section. In the channel section with a length of 34–44 mm, the magnetic field induction gradient reaches 1.17 T/m, which is almost twice the corresponding value for the classical scheme.

In conventional designs of Hall-effect thrusters without magnetic shielding [2–4, 7], the shape of the magnetic field distribution is determined by the geometry of the poles and the ratio of currents in the coils. The proposed variant of the magnetic screen allowed us to purposefully change the field topology without radically changing the main elements of the magnetic system. This provides advantages in the form of an increased magnetic field gradient and displacement of the maximum of the magnetic field induction beyond the engine section.

The results of modeling the topology of the magnetic field in the accelerating channel of the Hall-effect thruster with a magnetic shield in the form of a magnetically soft hollow anode (Fig. 8) confirm the effectiveness of such a design solution. In this case, a symmetrical distribution of the magnetic field relative to the channel axis is ensured and the magnetic field induction gradient increases further compared to the first variant of magnetic shielding.

The constructed plots of the magnetic field induction distribution along the channel axis with different positions of the hollow anode (Fig. 9) demonstrate the sensitivity of the magnetic field topology to the geometric position of the anode relative to the channel base. The maximum magnitude of the magnetic field induction gradient in the region of 34–44 mm reaches approximately 1.29 T/m, which is about 9% higher than the corresponding value for the first variant of magnetic shielding.

Unlike schemes in which magnetic shielding is implemented by additional elements outside the channel, the use of a hollow anode as an element of the magnetic system makes it possible to combine the functions of the anode and the formation of the required topology of the magnetic field. It is this design feature that provides an additional advantage of the proposed solution.

Our modeling results (Fig. 6–9) showed that the use of magnetic shielding, in particular in the variant with a hollow anode, makes it possible to implement all the specified requirements. This confirms the achievement of the research goal and indicates that the proposed design solutions effectively fill the existing niche between classical Hall-effect thruster schemes and more complex multi-component magnetic shielding systems.

The results allow us to eliminate the uncertainty identified in modern studies regarding the quantitative relationship between the design parameters of the magnetic system and the spatial distribution of the radial component of the magnetic field in the accelerating channel. Within the framework of the performed modeling, the regularities of the change in the induction gradient and the position of the magnetic field maximum were established depending on the configuration of the magnetic system and the magnetic shielding variant. This creates a basis for predicting the conditions for reducing wall erosion and increasing the stability of engine operating modes at the design stage. The results are adequate within the framework of the adopted simplifications: two-dimensional axisymmetric model, linear magnetic characteristics of materials, no plasma effect on the field distribution. When applying the results in practice, it is necessary to take into account that real engine operating conditions could lead to a change in the effective topology of the magnetic field.

The shortcomings of our research include the lack of self-consistent consideration in the model of plasma processes, temperature effects, and possible changes in the magnetic properties of materials under conditions of long-term engine operation. These factors may limit the possibility of directly transferring the results to real experimental samples without additional verification.

Further development of the research should be directed towards combining magnetic modeling with plasmodynamic models of the Hall discharge, as well as experimental verification of the results on laboratory engine samples. Of particular interest is the optimization of the geometry of the hollow anode and the parameters of the magnetic system, taking into account actual operating modes.

7. Conclusions

1. For the classical Hall-effect thruster ST-40, a computational model of the magnetic system was built and mathematical modeling of the topology of the magnetic field in the accelerating channel was performed. As a result, the distribution of the radial component of the magnetic field induction along the channel axis was obtained and the magnitude of the induction gradient in the region of maximum field values was determined. It was shown that, provided that the number of ampere-turns of the inner and outer coils is equal, a symmetric topology of the mag-

netic field is ensured relative to the channel axis in the absence of saturation of the magnetic circuit elements. A feature of our result is the establishment of a basic level of the magnetic field induction gradient for the classical motor circuit, which could be used as a standard for assessing the effectiveness of magnetic shielding. The obtained characteristics are explained by the geometry of the magnetic system and the uniform distribution of the magnetic flux between the magnetic circuit elements.

2. For the ST-40MS Hall-effect thruster with magnetic shielding of the accelerating channel, two structural variants of the magnetic system were implemented and analyzed – with an external magnetic shield and using a soft magnetic hollow anode. The simulation results showed that both variants of magnetic shielding provide a significant change in the topology of the magnetic field compared to the classical scheme, in particular, an increase in the magnetic field induction gradient along the channel axis and the removal of the maximum induction beyond the engine section. The greatest effect was achieved in the case of using a hollow anode, for which an additional increase in the induction gradient was recorded compared to the first shielding variant. A distinctive feature of this result is the combination of the functions of magnetic shielding and anode in one structural element, which allows for more efficient formation of the magnetic field without complicating the magnetic system. The obtained effects are explained by the shunting of the magnetic flux by the hollow anode and the redistribution of magnetic lines of force along the accelerating channel.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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Authors' contributions

Olexandr Petrenko: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – Original draft, Writing – Review & Editing, Visualization; **Viktor Pererva:** Validation, Investigation, Data curation, Writing – Original draft, Writing – Review & Editing.

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